

## Soft Gamma Repeaters and Anomalous X-ray Pulsars: Together Forever

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**Abstract.** I review of the observational properties of Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs), two unusual manifestations of neutron stars. I summarize the reasoning for SGRs being “magnetars,” neutron stars powered by the decay of a very large magnetic field, and the now compelling evidence that SGRs and AXPs are in fact members of the same source class, as predicted uniquely by the magnetar model. I discuss some open issues in the magnetar model, and the prospects for future work.

### 1. Introduction

Since Baade & Zwicky made their now-famous 1934 prediction regarding the existence of neutron stars, these amazing objects have not ceased to surprise us in the variety of their observational manifestation. Apart from thermal X-ray emission from initial cooling, predicted early on and now detected in a small handful of sources, the emission properties of neutron stars have been formally unpredicted, and informally unimagined.

The objects today being identified as “magnetars” are no exception. These sources literally exploded onto the astronomy scene in March 5, 1979, when the object today known as SGR 0525–66 emitted a soft-gamma-ray burst so intense that it saturated every gamma-ray detector that saw it (Mazets et al. 1979), likely measurably affected the Earth’s ionosphere, and implied an awe-inspiring  $> 10^6$  Eddington luminosities. This and the other handful of known “Soft Gamma Repeaters” (SGRs) prompted model explanations that ranged from vibrating neutron stars to strange star/pulsar phase transitions. Duncan & Thompson (1992), and quasi-simultaneously, Paczyński (1992), came up with the magnetar hypothesis, summarized below, which, particularly following seminal papers by Thompson & Duncan (1995, 1996), has uniquely stood the tests of increasingly constraining SGR observations. They also identified “Anomalous X-ray Pulsars” (AXPs) as additional members of the magnetar club. Though at the time having little in obviously common with SGRs, the AXPs, as we discuss below, have recently revealed themselves to be true siblings of the SGRs, with so many properties in common that the question to be answered today is “what differentiates them from SGRs?”

Table 1. Summary of Known and Candidate SGRs and AXPs

Name	$P$ (s)	$\dot{P}^a$ ( $\times 10^{-11}$ )	$\tau_c^b$ (kyr)	$B^c$ ( $\times 10^{14}$ G)	SNR?
SGRs <sup>d</sup>					
SGR 0525–66	8	?	?	?	N49
SGR 1627–41	6.4?	?	?	?	no
SGR 1801–23	?	?	?	?	?
SGR 1806–20	7.5	2.8	4.2	4.6	no
SGR 1808–20?	?	?	?	?	?
SGR 1900+14	5.2	6.1	1.3	5.7	no
AXPs <sup>e</sup>					
CXOU J0110043.1–721134?	8.0	?	?	?	no
4U 0142+62	8.7	0.20	69	1.3	no
1E 1048.1–5937	6.4	3.3	3.0	4.7	no
RX 1708–4009	11.0	1.9	9.2	4.6	no
XTE J1810–197?	5.5	1.1?	7.6?	2.5?	no
1E 1841–0450	11.8	4.1	4.6	7.0	Kes 73
AX 1845–0258?	7.0	?	?	?	G29.6+0.1
1E 2259+586	7.0	0.048	230	0.6	CTB 109

Note that “?” denotes an unknown or uncertain entry.

<sup>a</sup>Long-term average value. <sup>b</sup>Characteristic age estimated from  $P/2\dot{P}$ .

<sup>c</sup>Surface dipolar magnetic field estimated from  $3.2 \times 10^{19} (P\dot{P})^{1/2}$  G.

<sup>d</sup>References for all SGRs can be found in Hurley (2000), except for the candidate SGR 1808–20, which was reported by Lamb et al. (2003).

<sup>e</sup>References for all AXPs can be found in Mereghetti et al. (2002), except for CXOU J0110043.1–721134 which was reported by Lamb et al. (2002), and XTE J1810–197, reported by Markwardt et al. (2003).

## 2. The Observational Properties of Soft Gamma Repeaters

There are currently 4 and possibly 6 SGRs known (see Table 1), all but one of which are in the Galactic plane, the exception being in the Large Magellanic Cloud. The latter is in the direction of the supernova remnant N49, yet none of the others has been conclusively linked to a remnant (Gaensler et al. 2001). SGRs have as their hallmark repeating short ( $\sim 100$  ms) soft-gamma-ray and X-ray bursts, which have typical energies  $\sim 10^{41}$  erg, and rise times on the order of  $\sim 10$  ms (e.g. Göğüs et al. 1999). Burst spectra are generally well modelled by optically thin thermal bremsstrahlung models with  $kT \simeq 20 - 50$  eV (e.g. Göğüs et al. 1999). SGR bursting behaviour is highly episodic, with years of inactivity and weeks in which hundreds of bursts are detected. Occasionally, SGRs exhibit giant gamma-ray bursts having energies  $> 4 \times 10^{44}$  erg and luminosities  $> 4 \times 10^{44}$  erg s $^{-1}$ , well beyond the expectations of any distribution of the smaller bursts. Only two such giant bursts have been observed, the first in 1979 from SGR 0525–66 (Mazets et al. 1979), and the second from SGR 1900+14 in 1998 August (Hurley et al. 1999).

The three SGRs which have been securely seen to pulse have periods that range from 5 to 8 s. Two of the three exhibit these pulsations in quiescence in X-rays, and have clearly been shown to be spinning down (Kouveliotou et al. 1998, 1999). Under the assumption of simple magnetic dipole braking in a vacuum, the periods and period derivatives imply surface fields of  $\sim 10^{15}$  G. The pulsations have broad profiles. At the time of the 1998 giant burst of SGR 1900+14, its pulse profile abruptly changed from having multi-peaked structure to being much simpler (Kouveliotou et al. 1999). SGR spectra in quiescence are much softer than are the bursts, with power laws of photon index 2 – 3 typical. They are noisy rotators, resisting phase-coherent timing over spans longer than a few weeks (Woods et al. 2002). The bursting and rotational behavior do not appear well correlated, although at the time of the 1998 event, SGR 1900+14 showed evidence for a possible step down in frequency (Woods et al. 1999). There are no confirmed detections of any SGRs outside the X-ray or soft-gamma-ray band.

For more detailed reviews of SGRs, see Hurley (2000) or Thompson (2001).

### 3. SGRs as Magnetars

Thompson & Duncan (1995) presented many lines of reasoning pointing to the SGR bursts and quiescent emission being powered by the active decay of an ultra-high magnetic field. Here we summarize briefly the major points:

1. *From the 1979 event, which came from the direction of a supernova remnant and in which the decaying light curve was modulated by an 8-s periodicity, a high  $B$  field is needed to slow down a neutron star from a  $\sim 10$  ms period at birth within the  $\sim 10^4$  yr lifetime of a supernova remnant.* This argument predicted the subsequently observed spin downs of SGRs 1806–20 and 1900+14 which has provided the magnetar model with its greatest support. A possible spin down of SGR 0525–66 has also been reported (Kulkarni et al. 2003).
2. *An energy source well beyond what is available from either rotation or accretion is needed.* The luminosity of the bursts and quiescent emission is orders of magnitude greater than the  $\sim 10^{33}$  erg s $^{-1}$  available from rotation. Accretion is not viable given the apparent absence of any companion, the fact that such behaviour is unseen in any known accreting system, and because the accreting plasma would have to be very “clean” (i.e. pure photon/pair) to ensure low enough scattering depth for the hard burst spectra. For the energy of the giant bursts to be a small fraction of available magnetic energy,  $B \gtrsim 10^{15}$  G is required.
3. *For confinement of the emission in hyper-Eddington bursts, a magnetar strength field is required.* The light curves of the giant bursts include a hard, rapid-rise initial spike, followed by a quasi-exponential decay on a time scale minutes. The energy in the tail was much several times that in the initial spike, implying an event that released energy which was somehow confined for the hundreds of seconds. Magnetic confinement, if  $B \sim 10^{15}$  G, can do it.
4.  *$B > 10^{14}$  G can reduce the Thomson cross section and allow hyper-Eddington bursts.* The strong field greatly suppresses the electron cross section and the consequent decrease in scattering opacity allows higher fluxes to escape.

5.  $A \sim 10^{14} - 10^{15}$  G field can undergo active decay in a neutron star. Goldreich & Reisenegger (1992) showed that fields with strengths below these values are not expected to decay, while those above do via ambipolar diffusion in the core and Hall drift in the crust on  $\sim 10^4$  yr time scales.

In the magnetar picture, the quiescent X-rays originate from the surface, a result of internal heating from the decaying magnetic field. The bursts result from crust cracking under magnetic stress.

#### 4. Anomalous X-ray Pulsars

The nature of anomalous X-ray pulsars (AXPs) was a mystery since the discovery of the first example (Fahlman & Gregory 1981). There are currently only five confirmed AXPs, all of which are in the Galactic plane, with two at the centers of supernova remnants. Additionally there are three AXP candidates under investigation. All are listed in Table 1. AXPs exhibit X-ray pulsations with periods in the range 6–12 s, with luminosities in the range  $\sim 10^{33} - 10^{35}$  erg s $^{-1}$ . All are observed to be spinning down, with no evidence for Doppler shifts of the pulse periods. They have broad pulse profiles, and X-ray spectra that are soft compared to most accreting X-ray pulsars' and best described by two components (usually taken to be a blackbody having  $kT \simeq 0.4$  keV plus a hard power-law tail having photon index 2.5 – 4). Several AXPs have now been detected at optical/IR wavelengths. This is discussed in detail elsewhere in the proceedings (Israel et al.). For a lengthier review of AXPs, see Mereghetti et al. (2002).

AXPs were dubbed “anomalous” because it was unclear what powers their radiation. Rotation is insufficient by orders of magnitude in most sources. AXPs were long thought to be accreting from a low-mass companion (e.g. Mereghetti & Stella 1995). However this model is difficult to reconcile with observations: the absence of Doppler shifts, the absence of a detectable optical/IR companion, the apparent associations with supernova remnants, that AXP spectra are very different from those of known accreting sources, and that  $L_x$  is generally smaller than in known accreting sources, all are inconsistent with this scenario. Chatterjee et al. (2000) and Alpar (2001) considered a model in which AXPs are accreting from disks made of supernova fall-back material. In this case the similarity of source properties with those of SGRs is coincidental as no bursting mechanism is proposed, and in any case, recent optical/IR observations do not favour this possibility (see Israel et al., this volume).

Thompson & Duncan (1996) suggested that the main source of free energy for AXP emission is from the high magnetic fields ( $10^{14} - 10^{15}$  G) inferred from the rotation under standard assumptions. The implied low characteristic ages (Table 1) are supported by the associations with supernova remnants, and from the location of AXPs in the Galactic plane. The identification of AXPs with magnetars was more recently supported by the similarity of AXP emission to that of SGRs in quiescence; specifically, they have similar pulse periods, spin-down rates, and quiescent X-ray spectra. As of 1998, the only major distinction between the properties of SGRs and AXPs appeared to be that SGRs exhibited bursts while AXPs did not. However, other small distinctions exist: on average, the AXP spectra are softer than are those of the SGRs (e.g. Kulkarni et al.

2003); the SGRs are noisier rotators than the AXPs (Woods et al. 2002; Gavriil & Kaspi 2002); the frequency of association with a supernova remnant is higher for AXPs (Gaensler et al. 2001); and SGRs on average have higher inferred  $B$  fields than those of AXPs (Table 1).

## 5. SGR-Like Bursts from AXPs

As part of a major, long-term project to monitor all confirmed AXPs using the Proportional Counter Array aboard the *Rossi X-ray Timing Explorer* (see Gavriil & Kaspi 2002 and references therein), we have recently discovered SGR-like bursts from the direction of two AXPs.

The first discovery was of two bursts, separated by 16 days, from the direction of 1E 1048.1–5937 (Gavriil, Kaspi, & Woods 2002). Specifically, their fast rise times, short durations, hard spectra relative to the quiescent emission, fluence and probably clustering, are all SGR burst hallmarks. Note that the origin of the bursts could not unambiguously be proven to be the AXP, given the large PCA field-of-view, and the absence of any other radiative or spin change in the source. Intriguingly, the first burst’s spectrum was not well fit by a continuum model, showing evidence for a strong emission line at  $\sim 14$  keV.

The second discovery was unambiguous: in 2002 June, we detected over 80 bursts from 1E 2259+586 in a span of  $\sim 15$  ks (Kaspi et al. 2003). Figure 1 shows the light curve, as well as several properties of the persistent and pulsed emission during and following the outburst. Practically *every* aspect of the pulsed emission changed: the flux showed a large (order of magnitude) enhancement with fast (few day) and slow (months) decay components; the spectrum hardened but recovered within  $\sim 3$  days; the pulsed morphology changed during the outburst but relaxed back to near its pre-outburst shape after  $\sim 1$  week; and the pulsed fraction decreased during the outburst to  $\sim 2/3$  of its pre-outburst value, but recovered within  $\sim 6$  days. Furthermore, the pulsar suffered a possibly resolved rotational glitch, consisting of a sudden spin up ( $\Delta P/P = 4.2 \times 10^{-6}$ ), followed by a large (factor of  $\sim 2$ ) increase in the absolute magnitude of the spin-down rate (Fig. 2). See Woods et al. (2003) for a detailed analysis of all the above changes. In addition, an infrared enhancement was observed immediately post-outburst (Kaspi et al. 2003).

Overall, the properties of the outburst in 1E 2259+586 argue that the star suffered a major event that was extended in time and had two components, one tightly localized on the surface of the star (i.e. a fracture or a series of fractures) and the second more broadly distributed (possibly involving a smoother plastic change). The glitch points toward a disturbance within the superfluid interior while the extended flux enhancement and pulse profile change suggest an excitation of magnetospheric currents and crustal heating.

This AXP outburst was qualitatively and quantitatively similar to those of SGRs. However, there were some notable differences that may be clues to the physical differences between the two source classes. Specifically: the AXP bursts exhibit a wider range of durations and, unlike SGR bursts, occur preferentially near pulse maxima; the correlation between burst fluence and duration seen for SGRs is flatter than for AXPs; the AXP bursts are on average less energetic than are SGR bursts; and the more energetic AXP bursts have the hardest spectra –

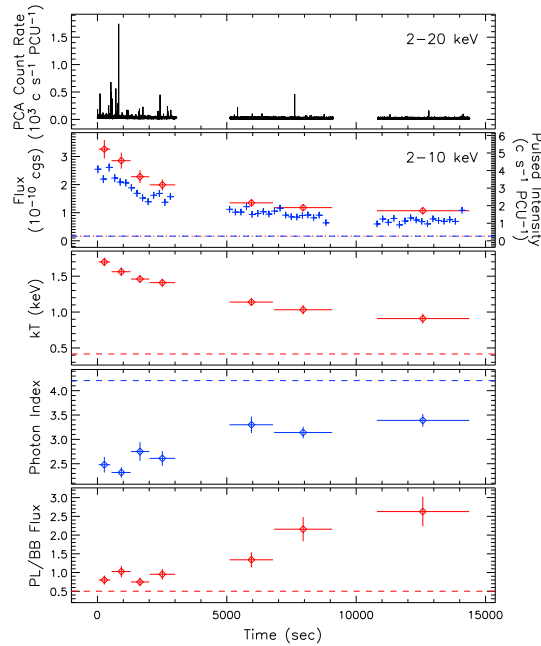


Figure 1. Light curve and evolution of persistent and pulsed emission during the 1E 2259+586 outburst. Top panel: 2–20 keV light curve at 0.125-s resolution. 2nd panel: unabsorbed persistent (diamonds) and pulsed (crosses) fluxes (2–10 keV). The horizontal dashed (dotted) lines denote the quiescent levels of each parameter. 3rd panel: blackbody temperature of the persistent and pulsed emission assuming a two-component (blackbody and power-law) model. 4th panel: power-law photon index of the persistent and pulsed emission. 5th panel: ratio of the unabsorbed 2–10 keV power-law flux and the bolometric blackbody flux (from Kaspi et al. 2003).

the opposite of what is seen for SGRs (Gavriil, Kaspi & Woods, in preparation). Furthermore, in stark contrast to SGRs, the energy detected in bursts ( $6 \times 10^{37}$  erg, 2–60 keV) was much smaller than that in the post-outburst persistent flux enhancement ( $2 \times 10^{41}$  erg, 2–10 keV). This could indicate bursting activity that was missed by our observations and the gamma-ray monitors (Woods et al. 2003). No matter what, this “quiet” outburst strongly suggests there are many more such objects in the Galaxy than was previously thought.

## 6. Conclusions and Open Issues

The discovery of SGR-like bursts from 1E 1048.1–5937 and especially 1E 2259+586 solidifies the common nature of AXPs and SGRs as predicted uniquely by the magnetar model. This model has now made two major predictions, namely the

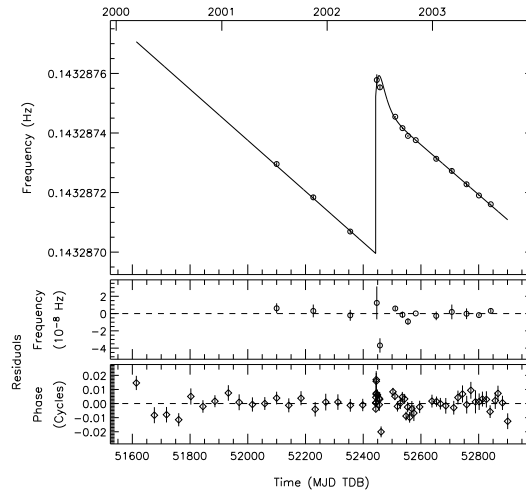


Figure 2. Frequency evolution of 1E 2259+586 around the 2002 outburst for a model including an extended exponential rise and fall in frequency post-glitch. Top panel: the solid line represents the best-fit model. The circles denote frequency measurements. Middle panel: the frequency residuals. Bottom panel: phase residuals with respect to the best-fit model (from Woods et al. 2003).

spin-down of SGRs and the common nature of AXPs and SGRs, both of which have been unambiguously borne out by observations. The magnetar hypothesis thus appears to be very compelling.

However, there is still no direct evidence for the magnetar strength fields. Such evidence could in principle be obtained from the detection of cyclotron lines in SGR or AXP spectra. Spectral features detected in some SGR and AXP bursts may well be providing us with an important clue (Ibrahim et al. 2002; Gavril et al. 2002) but their interpretation remains unclear as of yet.

Further, one expects a magnetar/radio pulsar connection. This could come in two ways. One is to detect radio pulsations from an AXP or SGR. Such detections have been claimed but not confirmed (see paper by XXX, this volume). However, detecting radio pulsations may be impossible; the long spin periods imply small polar caps, hence very narrow radio beams. Alternatively, QED processes at high  $B$ , such as photon splitting, may preclude the electron/positron cascades necessary to produce radio emission (Baring & Harding 2001). Another way to prove a magnetar/radio pulsar connection is to detect enhanced X-ray emission from a high- $B$  radio pulsar. This has not yet been done even though several radio pulsars (see McLaughlin et al., this volume) have now been found having inferred  $B$  comparable to or higher than that of 1E 2259+586, yet with no evidence for excess X-ray emission. This is puzzling, but may simply reflect that our  $B$  estimate is, in reality, not very accurate. Continued discoveries of high- $B$  radio pulsars should prove interesting.

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